A Measurement of the Branching Fraction of D_s Inclusive Semileptonic Decay $D_s^+ \to e^+ X$

J. Z. Bai,[1] O. Bardon,[5*] I. Blum,[10] A. Breakstone,[8] T. Burnett,[11] J. S. Campbell,[10] G. P. Chen,[1] H. F. Chen,[3] J. Chen,[4] S. J. Chen,[1] S. M. Chen,[1] Y. Chen,[1] Y. B. Chen,[1] Y. Q. Chen,[1] B. S. Cheng,[1] R. F. Cowan,[5] X. Z. Cui,[1] H. L. Ding,[1] Z. Z. Du,[1] W. Dunwoodie,[7] X. L. Fan,[1] J. Fang,[1] M. Fero,[5] C. S. Gao,[1] M. L. Gao,[1] S. Q. Gao,[1] P. Gratton,[10] J. H. Gu,[1] S. D. Gu,[1] W. X. Gu,[1] Y. F. Gu,[1] Y. N. Guo,[1] S. W. Han,[1] Y. Han,[1] F. A. Harris,[8] J. He,[1] M. He,[6] D. G. Hitlin,[2] G. Y. Hu,[1] T. Hu,[1] X. Q. Hu,[1] D. Q. Huang,[1] Y. Z. Huang,[1] J. M. Izen,[10] Q. P. Jia,[4] C. H. Jiang,[1] S. Jin,[1] Y. Jin,[1] L. Jones,[2] S. H. Kang,[1] Z. J. Ke,[1] M. H. Kelsey,[2] B. K. Kim,[10] D. Kong,[8], Y. F. Lai,[1] H. B. Lan,[1] P. F. Lang,[1] A. Lankford,[9] F. Li,[1] J. Li,[1] P. Q. Li,[1] Q. Li,[6] R. B. Li,[1] W. Li,[1] W. D. Li,[1] W. G. Li,[1] X. H. Li,[1] X. N. Li,[1] S. Z. Lin,[1] H. M. Liu,[1] J. Liu,[1] J. H. Liu,[1] Q. Liu,[1] R. G. Liu,[1] Y. Liu,[1] Z. A. Liu,[1] X. C. Lou,[10] B. Lowery,[10] J. G. Lu,[1] J. Y. Lu,[1] S. Luo,[1] Y. Luo,[1] A. M. Ma,[1] E. C. Ma,[1] J. M. Ma,[1] H. S. Mao,[1] Z. P. Mao,[1] R. Malchow,[4] M. Mandelkern,[9] X. C. Meng,[1] H. L. Ni,[1] J. Nie,[1] S. L. Olsen,[8] J. Oyang,[2] D. Paluselli,[8] L. J. Pan,[8] J. Panetta,[2] F. Porter,[2] E. Prabhakar,[2] N. D. Qi,[1] Y. K. Que,[1] J. Quigley,[5] G. Rong,[1] M. Schernau,[9] B. Schmid,[9] J. Schultz,[9] Y. Y. Shao,[1] D. L. Shen,[1] H. Shen,[1] X. Y. Shen,[1] H. Y. Sheng,[1] H. Z. Shi,[1] X. R. Shi,[2] E. Soderstrom,[7] X. F. Song,[1] J. Standifird,[10] D. Stoker,[9] F. Sun,[1] H. S. Sun,[1] S. J. Sun,[1] J. Synodinos,[7] Y. P. Tan,[1] S. Q. Tang,[1] W. Toki,[4] G. L. Tong,[1] F. Wang,[1] L. S. Wang,[1] L. Z. Wang,[1] M. Wang,[1] P. Wang,[1] P. L. Wang,[1] S. M. Wang,[1] T. J. Wang,[1] Y. Y. Wang,[1] M. Weaver,[2] C. L. Wei,[1] W. J. Wisniewski,[7] D. M. Xi,[1] X. M. Xia,[1] P. P. Xie,[1] D. Z. Xu,[1] R. S. Xu,[1] Z. Q. Xu,[1] S. T. Xue,[1] J. Yan,[1] W. G. Yan,[1] C. M. Yang,[1] C. Y. Yang,[1] H. Yang,[10] W. Yang,[1] M. H. Ye,[1] S. Z. Ye,[1] K. Young,[11] C. S. Yu,[1] C. X. Yu,[1] Z. Q. Yu,[1] C. Z. Yuan,[1] B. Y. Zhang,[1] C. C. Zhang,[1] D. H. Zhang,[1] H. L. Zhang,[1] J. Zhang,[1] J. W. Zhang,[1] L. S. Zhang,[1] S. Q. Zhang,[1] Y. Zhang,[1] Y. Y. Zhang,[1] D. X. Zhao,[1] J. W. Zhao,[1] M. Zhao,[1] W. R. Zhao,[1] J. P. Zheng,[1] L. S. Zheng,[1] Z. P. Zheng,[1] G. P. Zhou,[1] H. S. Zhou,[1] L. Zhou,[1] X. F. Zhou,[1] Y. H. Zhou,[1] Q. M. Zhu,[1] Y. C. Zhu,[1] Y. S. Zhu,[1] B. A. Zhuang,[1]
(BES Collaboration)[†]

[1] *Institute of High Energy Physics, Beijing 100039, People's Republic of China*
[2] *California Institute of Technology, Pasadena, California 91125*
[3] *China's University of Science and Technology, Hefei 230026, People's Republic of China*
[4] *Colorado State University, Fort Collins, Colorado 80523*
[5] *Massachusetts Institue of Technology, Cambridge, Massachusetts 02139*
[6] *Shandong University, Jinan 250100, People's Republic of China*
[7] *Stanford Linear Accelerator Center, Stanford, California 94309*
[8] *University of Hawaii, Honolulu, Hawaii 96822*
[9] *University of California at Irvine, Irvine, California 92717*
[10] *University of Texas at Dallas, Richardson, Texas 75083-0688*
[11] *University of Washington, Seattle, Washington 98195*

(July 22, 1996)

The absolute inclusive semileptonic branching fraction of D_s meson has been measured based on 22.3 pb^{-1} of e^+e^- collision data collected with BES at $\sqrt{s} = 4.03$ GeV$/c^2$. At this energy, D_s are produced in pairs: $e^+e^- \to D_s^+ D_s^-$. We reconstructed $147 \pm 19 \pm 13$ D_s decay events in four hadronic decay modes. In the recoil system of these events, several D_s inclusive semileptonic decays were observed, and the branching fraction was estimated to be $B(D_s^+ \to e^+ X) = 6.2^{+6.6+2.4}_{-4.8-2.1}\%$.

The spectator model predicts equal lifetimes for D^+, D^0, and D_s^+. This prediction is incorrect; the D^+ lifetime is about twice as long as that of the D^0 and the D_s^+ [1]. The inequality is believed to be due to final state interference in hadronic D^+ decays; the semileptonic decay widths are still expected to be approximately equal, *i.e.*, $\Gamma_{SL}(D^+) \approx \Gamma_{SL}(D^0) \approx \Gamma_{SL}(D_s^+)$. The inclusive electronic semileptonic branching fractions of the D^+, $B(D^+ \to e^+X) = (17.2 \pm 1.9)\%$, and D^0, $B(D^0 \to e^+X) = (7.7 \pm 1.2)\%$, [1] are consistent with $\Gamma_{SL}(D^+) \approx \Gamma_{SL}(D^0)$ considering the difference in lifetimes. If this relation extends to the D_s, then $B(D_s^+ \to e^+X)$ should be about 8%. This branching fraction was measured by MARK-III at $\sqrt{s} = 4.14$ GeV$/c^2$ with a fairly large error, resulting in an upper limit of 20% at 90% C.L. [2]. Since then, progress has been achieved only on some exclusive D_s semileptonic decay modes both experimentally [3–5] and theoretically [6–8].

This paper reports a new measurement of the inclusive D_s semileptonic branching fraction with data collected with the Bejing Spectrometer (BES) at $\sqrt{s} = 4.03$ GeV$/c^2$, just above the $e^+e^- \to D_s^+ D_s^-$ threshold. We detect one of the two D_s via its hadronic decay into $\phi\pi^+$, $\bar{K}^{*0}K^+$, $K_S^0 K^+$, or $K_S^0 K^- \pi^+ \pi^+$, and search the recoil system for semileptonic decays with one well identified electron track. Charge conjugate decay modes are implicitly assumed throughout this paper.

The BES detector is designed to identify electrons, photons, pions, kaons and muons [9]. The charged track momentum resolution is $\sigma_p/p = 0.017\sqrt{1+p^2}$ (p in GeV/c). Time resolution in the time of flight (TOF) counters for Bhabha events is about 380 ps. Energy loss (dE/dx) measurement in the main drift chamber (MDC) with a resolution of 8.5% is used for π/K separation along with TOF. The barrel shower counter (BSC) with an energy resolution of $\Delta E/E = 25\%/\sqrt{E}$ is used to detect photons, and to separate electrons and hadrons together with TOF and dE/dx.

Data were taken during 1992-1994 at the BEPC. The trigger requires at least one barrel TOF hit within a time window of 40 ns around beam crossing, one hit in the outer two layers of the central drift chamber, one charged track found by the online trigger logic using the hit pattern in the MDC, and a total energy in the BSC above 200 MeV. The luminosity is calculated based on large angle Bhabha events.

At $\sqrt{s} = 4.03$ GeV/c^2, D_s mesons can only be produced via $e^+e^- \to D_s^+D_s^-$. The total energy of a D_s candidate equals to the beam energy $E_{beam} = 2.015$ GeV/c^2. Hence the beam-energy-constraint can be imposed on the measured momenta of D_s daughter particles via a kinematic fit (a 1-C fit) to improve the measured D_s mass resolution. This constraint is applied in the analysis presented here.

The D_s mesons are reconstructed in four hadronic decay modes: $\phi\pi^+$, $\bar{K}^{*0}K^+$, $K_S^0K^+$, and $K_S^0K^-\pi^+\pi^+$, with subresonances decaying as $\phi \to K^+K^-$, $\bar{K}^{*0} \to K^-\pi^+$, and $K_S^0 \to \pi^+\pi^-$. Events are selected which contain at least three reconstructed charged tracks. In order to ensure good momentum resolution, all tracks used in the single tag are required to have a good helix fit in the MDC with a fiducial cut of $|\cos\theta| < 0.8$, and to originate from the production vertex. Pions consistent with K_S^0 decays are exempt from the vertex cut. Pions and kaons are identified by a combined confidence level of TOF and dE/dx measurements. Identification requires consistency with the pion or kaon hypothesis with a confidence level greater than 0.1%. In order to reduce misidentifications, all kaon candidates are further required to have a larger confidence level for the kaon hypothesis than that for pion hypothesis, except charged kaons in the $K_S^0K^+$ mode, since their momenta are too high which would lead to an unacceptable loss of efficiency.

Possible track combinations for each final state of the four D_s decay modes are subject to the 1-C kinematic fit; events with a probability $P(\chi^2) > 10\%$ are kept for further analysis. A requirement on the difference between the measured energy of the D_s candidate and the beam energy, $E_{diff} = E_{Ds} - E_{beam}$, effectively suppresses the background from D decay. The $|E_{diff}| < 50$ MeV is required in all modes except $K_S^0K^+$, where an asymmetric cut -50 MeV $< E_{diff} < 20$ MeV is imposed instead, because the kaon identification is poorer and meanwhile the E_{diff} distribution of D background, from $D \to K_S^0\pi$ with π mis-identified as K, is centered at the positive side in this mode. A mass cut on the subresonances ϕ, $\bar{K}^{*0}$, and K_S^0 further suppresses the background. We require $|M(KK) - M(\phi)| < 18$ MeV/c^2, $|M(K\pi) - M(K^{*0})| < 50$ MeV/c^2, and $|M(\pi\pi) - M(K_S^0)| < 22$ MeV/c^2. The polar angle, θ_h, in the $\bar{K}^{*0}$ helicity frame is restricted by $|\cos\theta_h| > 0.35$ to reduce background in the $\bar{K}^{*0}K^+$ mode. For the K_S^0 reconstruction, we require the momentum vector of the two oppositely charged pions to be aligned with the position vector of the secondary vertex in the xy plane with a confidence level greater than 10%. The secondary vertex is required to be at least 5 mm (in $K_S^0K^+$ mode) or 1.5 mm (in $K_S^0K^-\pi^+\pi^+$ mode) away from the collision point in xy plane, and the z coordinates of the two pion tracks to be within 4 cm of the secondary vertex, in order to reduce mis-matching pion pairs.

After the above cuts, D_s signals are clearly seen in the mass spectra (see Figure 1). The other peak beside D_s in $K_S^0K^+$ mode (Figure 1(c)), and hence the combined spectrum (Figure 1(e)), are due to $D^+ \to K_S^0\pi^+$ produced via $e^+e^- \to DD^*$, where the pion is misidentified as a kaon. These peaks can be reproduced by $e^+e^- \to DD^*$ Monte Carlo simulations. Fitting the mass spectra with a Gaussian (two Gaussians in Figure 1(c) and (e)) plus a second order polynomial background yields the number of tagged events for each of the four decay modes as well as the total number of single tags, $147 \pm 19 \pm 13$. The first error is statistical; the second error is systematic and is obtained by varying the parametrization of the background. The fitted D_s mass is 1968.7 ± 0.6 MeV/c^2 with a resolution of 3.9 ± 0.6 MeV/c^2.

The recoil system of the single tag D_s events is searched for a well identified electron track. Recoil electrons are required to have a momentum larger than 0.2 GeV/c. To ensure good tracking and particle ID information, tracks have to be within the fiducial volume of $|\cos\theta| < 0.75$ and they must have a good helix fit. In addition, a cut on the angle to the nearest, oppositely charged electron track, $\cos\theta_{ee} < 0.98$, is imposed to further reduce background from photon conversion.

The dE/dx, TOF and BSC information is used to calculate joint confidence levels for each particle hypothesis. In order to get a high electron ID efficiency and a low hadron misidentification rate, we require the confidence level for the electron hypothesis to be above 1%, and the confidence level for the pion and kaon hypothesis to be below 5%.

Radiative Bhabha events in the same dataset are used to measure the electron identification efficiency P_{ee}, and pions from kinematically selected $J/\psi \to \omega\pi\pi$ events are used to estimate the hadron misidentification probability $P_{\pi e}$. The measured P_{ee} and $P_{\pi e}$ vary slightly with momentum. The P_{ee} values are weighted by the electron momentum distribution of Monte Carlo simulated $D_s^+ \to e^+ X$ decays to obtain an average value of 82%. Similarly, the $P_{\pi e}$ is weighted with the measured momentum distribution of pions from inclusive D_s decays to yield an average of 0.8%. Further more, at least one additional charged or neutral track is required. This lowers the event selection efficiency by 1%, as determined from Monte Carlo simulation.

If the recoil track's charge is opposite to the tag's charge, the track is called Right Sign (RS). Otherwise, it is called Wrong Sign (WS). Figure 2(a) shows the single tag mass spectra when a RS and a WS electron is detected in the recoil system respectively. Figure 2(b) shows the single tag mass spectra when a RS and a WS hadron is detected in the recoil system respectively. The RS electron signal contains $D_s^+ \to e^+ X$ events, as well as $D \to eX$ background, hadrons misidentified as electrons, and the charge symmetric background from surviving gamma conversions and π^0 Dalitz decays. The charge symmetric background is reflected by the number of WS electrons. The number of hadrons misidentified as electrons can be estimated from the number of hadrons in the recoil system N_h, multiplied by the hadron mis-ID probability P_{he}. Here we approximate the misidentification probability of kaons to be equal to that of pions: $P_{he} \approx P_{Ke} \approx P_{\pi e} = 0.8\%$.

The corrected spectrum with charge symmetric backgrounds and hadron misidentifications subtracted is shown in Figure 2(c). Since the $D \to eX$ background is continuous and approximately flat (except for the enhancements at 1.94 GeV/c^2), the enhancement at 1.97 GeV/c^2 in Figure 2(c) is due to the D_s semileptonic decay.

After single tagging, the efficiency of the event selection is merely the detection efficiency of the electron track, which includes the fiducial cut acceptance, the momentum cut acceptance, the $\cos\theta_{ee} < 0.98$ acceptance, and the additional track requirement efficiency (99%). This leads to a geometric efficiency of $\varepsilon_{geom} = 64\%$, which is determined by Monte Carlo simulation. The Monte Carlo simulation consists of the three major semileptonic decay modes $\phi e\nu$, $\eta e\nu$, and $\eta' e\nu$, with relative branching ratios measured by CLEO II [5]. The uncertainty of the existence of other D_s exclusive semileptonic decays causes an error of $\sim 5\%$ in the determination of the efficiency.

The estimation of the branching fraction is based on the number of signal events in the histograms for the RS and WS electrons and hadrons, as well as the number of D_s tags. In each histogram, signal events follow a Gaussian distribution $f_1(x)$ centered at $x_0 = 1968.7 \pm 0.6$ MeV/c^2 with a standard deviation of $\sigma = 3.9 \pm 0.6$ MeV/c^2. The parameters are determined from a fit to the distribution of the single tags. In the same fit, the distribution of the background events is approximated by a quadratic function $f_2(x)$ for the combinatorial background plus a Gaussian distribution $f_3(x)$ centered at 1948.3MeV/c^2. All three functions are normalized to unit integral.

We set up an unbinned extended likelihood for the number of signal and background events (s, b_1 and b_2, respectively) in each histogram:

$$\mathcal{L}(s, b_1, b_2) = e^{-s-b_1-b_2} \prod_{i=1}^{N} [s f_1(x_i) + b_1 f_2(x_i) + b_2 f_3(x_i)]. \tag{1}$$

To obtain a likelihood for the number of signal events alone, we marginalize $\mathcal{L}(s, b_1, b_2)$ with respect to b_1 and b_2:

$$\mathcal{L}(s) = \int_0^\infty \int_{-\infty}^{\infty} \mathcal{L}(s, b_1, b_2)\, db_2\, db_1. \tag{2}$$

For both the electrons and the hadrons, we calculate the likelihood for the net number $N_{net} = N_{RS} - N_{WS}$ as a product of the two likelihoods $\mathcal{L}_{RS}(N_{RS})$ and $\mathcal{L}_{WS}(N_{WS})$ and marginalize it:

$$\mathcal{L}(N_{net}) = \int_{-\infty}^{\infty} \mathcal{L}_{RS}(N_{RS}) \mathcal{L}_{WS}(N_{RS} - N_{net})\, dN_{RS}. \tag{3}$$

Using the values for the particle identification probabilities, we correct the net number of electrons and obtain a likelihood for the true number of electrons, $N^e_{true} = (N^e_{net} - P_{he} N^h_{net})/P_{ee}$, and marginalize with respect to the number of hadrons. Finally, we calculate the branching fraction

$$Br(D_s \to e\nu X) = \frac{N^e_{true}}{\varepsilon_{geom} N_{tag}}. \tag{4}$$

Figure 3 shows the resulting likelihood as a function of the branching fraction. The shaded area on the left (right) corresponds to 31.73 % of the area under the curve on the left (right) side of the maximum. The unshaded region is the error interval. This leads to a semileptonic branching fraction of:

$$Br(D_s \to e\ X) = (6.2^{+6.6+2.4}_{-4.8-2.1})\%,$$

where the first error is statistical. The second error is systematic, mainly estimated on the basis of the changes of $Br(D_s \to e\ X)$ due to variations in the electron momentum cut ($\pm 1.9\%$), the shape of the background ($\pm 0.5\%$), the electron detection efficiency ($^{+0.5}_{-0.1}\%$), the hadron misidentification rate ($^{+0.9}_{-0.7}\%$), the width of the bump around 1.948 GeV/c^2 ($^{+0.4}_{-0.1}\%$) and the geometric efficiency ($^{+0.6}_{-0.2}\%$). The combined effect of these sources is obtained by adding in the uncertainties in quadrature, which yeilds a total systematic error of ($^{+2.4}_{-2.1}\%$).

Our measurement is consistent with the MARK-III [2] measurement, but has smaller errors. Considering the lifetimes of the charmed mesons given by PDG, our branching fraction corresponds to a D_s semileptonic decay width of $\Gamma(D_s^+ \to e^+X) = (1.32^{+1.41+0.51}_{-1.02-0.45}) \times 10^{11} s^{-1}$, while D^+ and D^0 measurements [1] lead to $\Gamma(D^+ \to e^+X) = (1.63 \pm 0.18) \times 10^{11} s^{-1}$ and $\Gamma(D^0 \to e^+X) = (1.86 \pm 0.29) \times 10^{11} s^{-1}$. The measured semileptonic decays of charmed mesons are consistent with the description of the spectator model, $\Gamma_{SL}(D^+) = \Gamma_{SL}(D^0) = \Gamma_{SL}(D_s^+)$.

We would like to thank the staff of BEPC accelerator and the IHEP Computing Center. We also thank Prof. Zhaoxi Zhang for useful discussions of D_s physics.

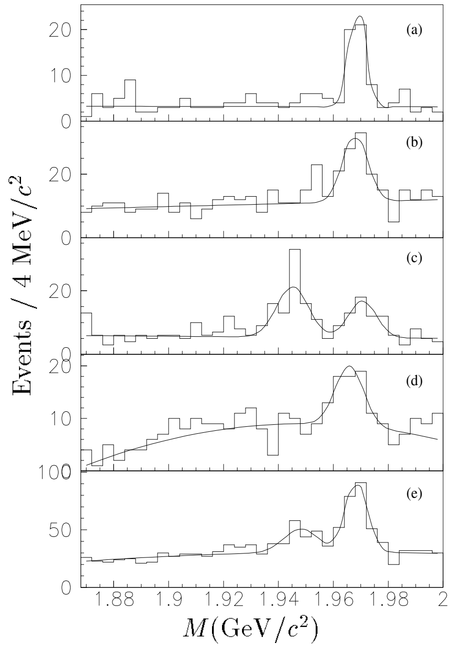

FIG. 1. Mass distribution of D_s single tags. (a) $\phi\pi^+$; (b) $\bar{K}^{*0}K^+$; (c) $\bar{K}^0_S K^+$; (d) $K^0_S K^-\pi^+\pi^+$; and (e) combined.

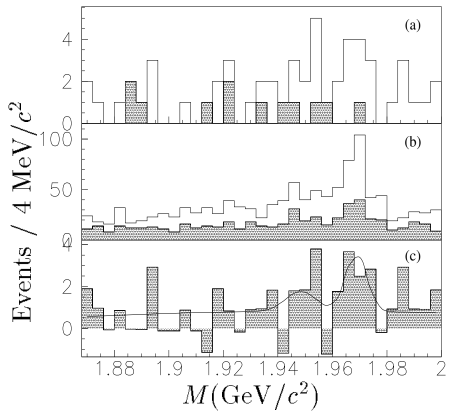

FIG. 2. (a) Single tag mass spectra when a RS (unshaded) and a WS electron (shaded) is detected in the recoil system. (b) Single tag mass spectra when a RS (unshaded) and a WS hadron (shaded) is detected in the recoil system. (c) Single tag mass spectrum of RS-WS electrons corrected for hadron misidenification.

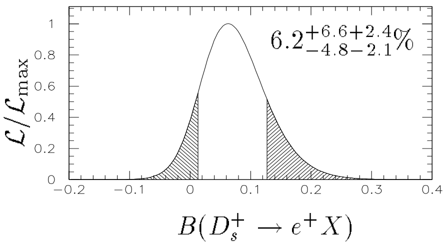

FIG. 3. Normalized likelihood versus branching fraction

* Present address: Northeastern University, Boston, MA.

† Work supported in part by the National Natural Science Foundation of China under Contract No. 19290400 and the Chinese Academy of Sciences under contract No. KJ85 (IHEP); by the Department of Energy under Contract Nos. DE-FG03-92ER40701 (Caltech), DE-FG03-93ER40788 (Colorado State University), DE-AC02-76ER03069 (MIT), DE-AC03-76SF00515 (SLAC), DE-FG03-91ER40679 (UC Irvine), DE-FG03-94ER40833 (U Hawaii), DE-FG03-95ER40925 (UT Dallas); by the U.S. National Science Foundation, Grant No. PHY9203212 (University of Washington); and by the Texas National Research Laboratory Commission under Contract Nos. RGFY91B5, RGFY92B5 (Colorado State), and RCFY93-316H (UT Dallas).

[1] PDG, Phys. Rev. D50(1994).
[2] Bai *et al.*, Phys. Rev. Lett. 65(1990)686.
[3] F. Butler *et al.*, Phys. Lett. B324(1994)255.
[4] K. Kodama *et al.*, Phys. Lett. B309(1993)483.
[5] G. Brandernburg *et al.*, preprint CLNS 95-1351.
[6] V. Lubicz, G. Mattineli, M. S. McCarthy & C. T. Sachrajda, Phys. Lett. B274(1992)415.
[7] D. Scora and N. Isgur, preprint CEBAF-TH-94-14.
[8] A. N. Kamal *et al.*, Phys. Rev. D49(1994)1330.
[9] J. Z. Bai, *et al.*, Nucl. Instr. Meth., A344(1994)319.